Development of Superconducting Accelerator Magnets at Fermilab

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- SC magnet R&D
- Material and component R&D

SC Magnet R&D program

Fermilab has a strong SC magnet R&D program, which is natural for a laboratory with the largest and highest-energy SC accelerator in the world, the Tevatron.

The goal of our SC Magnet R&D program is the development of new generation SC *accelerator* magnets with high operation fields and high operation margins for different applications.

A short list of possible applications includes:

- SC magnets for the Tevatron,
  - to replace some present dipoles in order to create space for special devices,
  - to replace existing IR quadrupoles with higher-gradient, larger aperture quadrupoles or create a new IR;
- SC magnets for a future Very Large Hadron Collider (VLHC);
- 2nd generation LHC IR dipoles and quadrupoles with larger apertures and higher operation margins for higher luminosity;
- SC magnets for beam transfer lines, etc.

Superconductor & Technology

Our present SC Magnet R&D program is focused on the accelerator magnets based on Nb3Sn superconductor. Present Nb3Sn strands:

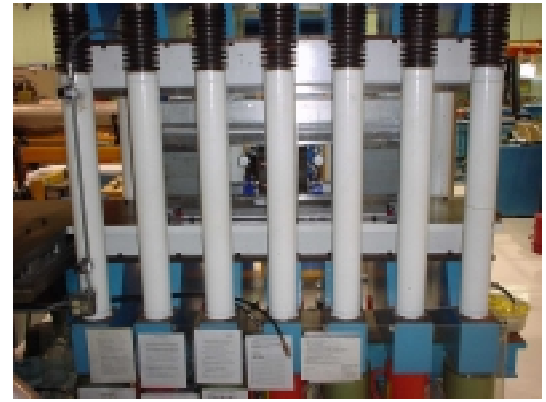
- have acceptable, continuously improving properties
- produced on the commercial level
- have reasonable price
- are brittle after reaction heat treatment

We explore two basic technologies for brittle superconductors:

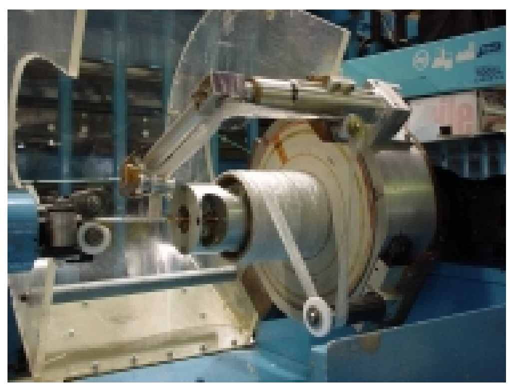
- wind-and-react
- react-and-wind

We are also looking after the other superconductors and technologies. We will start working with them as soon as they reach the level when they become interesting for application in accelerator magnets.

Magnet R&D Infrastructure



- Cable insulating machine
- Winding tables: (<2m,<15m)
- Coil HT oven and retorts (<1m)
- Epoxy impregnation facility (<6m)
- Collaring/yoking presses (<15m)
- Magnet test facilities (<4m,<15m)



Design approaches

Now we are investigating two types of high-field dipole designs for VLHC:

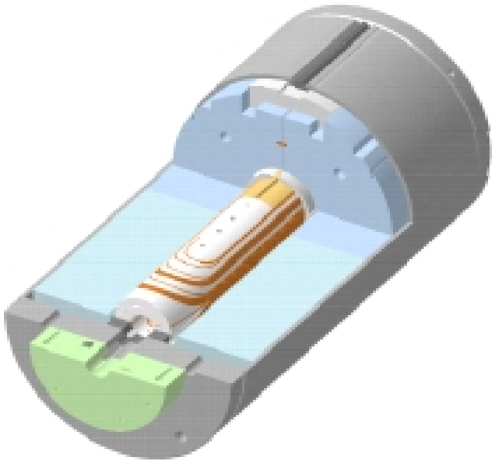
- One design is based on shell-type coils with a cos-theta azimuthal current distribution.
  - This design approach is implemented in almost all NbTi SC magnets used in present high-energy accelerators/colliders.
- The other design is based on flat block-type coils arranged in the common-coil configuration.
  - In this innovative design approach the coil radii are set by the aperture separation, not the aperture size, and hence, conductor bends are relatively gentle and friendly to brittle conductors.

Based on these basic design approaches we have developed several innovative dipole magnets for VLHC.

Cos-theta dipole models

A series of 1-m long single-bore models of cos-theta Nb3Sn dipole is being fabricated and tested.

- Nb3Sn high Jc superconductor
- traditional 2-layer coil
- Cold iron yoke
- wind-and-react technique
- nominal field of 12 T at 4.5 K
- accelerator field quality
- 43.5-mm diameter bore.



Four short models were fabricated and three of them were tested in FY2001-2002.

- achieved accelerator field quality
- not achieved yet the required field level.

Focus on the magnet quench performance.

The next 5th dipole model to be fabricated and tested in October, 2003.

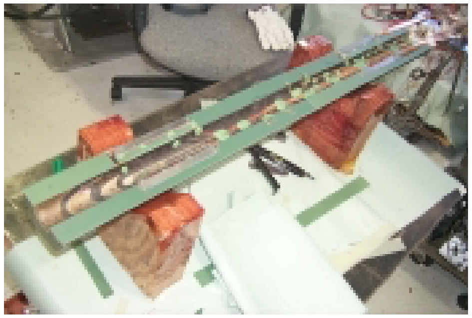
Magnetic mirror

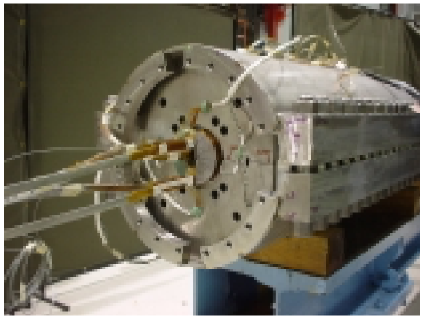
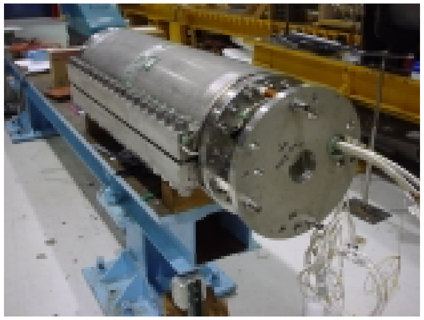
We are studying and optimizing the magnet technology and quench performance using half-coils and a magnetic mirror:

- same mechanical structure and assembly procedure
- advanced instrumentation
  - voltage taps, spot heaters, thermometers, strain gauges
- short turnaround time, cost effective
  - bolted skin, same yoke and spacers
- The 1st half-coil was tested with magnetic mirror in January, 2003.

The half-coil tests with magnetic mirror scheduled in March-May, 2003:

- splice tests using an old half-coil – assembly, mechanics, cooling, etc.
- 2 new half-coil tests – technology, quench performance, mechanics

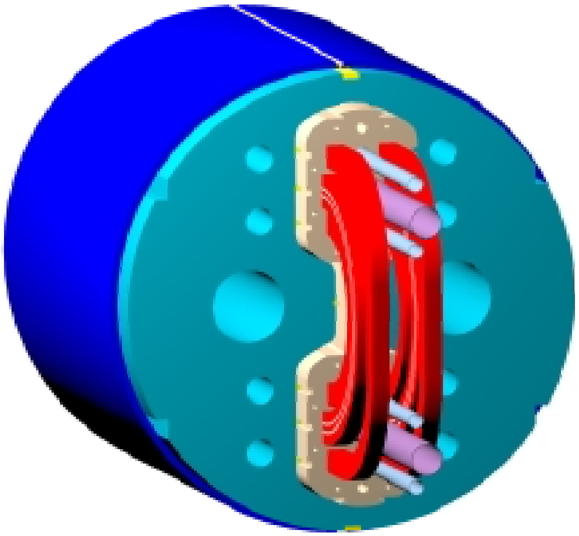


Common coil dipole

Fabrication and tests of 1-m long common coil dipole models have been started:

- single-layer coil
- cold yoke
- wide pre-reacted Nb_3Sn cable
- magnet bore of 40-50 mm
- advanced mechanical structure
- nominal field of 11 T at 4.5 K
- accelerator quality field



Mechanical and technological models have been fabricated in FY2002.

The 1st common coil short model is being fabricated and will be tested in May-June, 2003.

React & wind Nb3Sn racetracks

Experimental studies and optimization of react-and-wind techniques are performed using sub-sized cable and flat 1-m long racetrack coils.

Two react & wind Nb3Sn racetracks have been fabricated and tested in FY2001-2002.

- 2nd racetrack reached 78% of its short sample limit.

The 3rd racetrack, similar to the 2nd one, is being fabricated and will be tested in April, 2003.

HFDB03 features:

- Sub-sized cable – 41 strands, 0.7 mm
- Improved cable reaction procedure
- Insulation – Kapton/fiberglass tapes
- Improved mechanical structure
- Improved winding procedure & tooling
- Impregnation – epoxy in-situ
- Upgraded instrumentation

Production and test plans

We are planning production and test of 2-3 short model magnets per year.The goals are understanding and improvement of the magnet technologies and quench performance, and optimization of the field quality.

When basic problems are understood we plan to increase the production and tests of HFM models of different types to 5-6 per year with the goal to study and optimize the performance reproducibility and magnet cost.

We are also planning to develop infrastructure and start fabrication of long models starting in FY2005-2006.

LARP

Fermilab participates in the U.S. LHC Accelerator Research Program (LARP).

One of the LARP goals is to develop 2nd generation IR magnets for LHC to replace the 1st generation magnets:

- limited lifetime (~6 years)
- one of the limiting systems for machine performance

Contributions of Fermilab to LARP Magnet R&D include:

- conceptual designs studies of various magnet types for 2nd generation LHC IRs.
- Fermilab will also participate in short and long model magnet R&D as well as in the design, fabrication and tests of full-scale prototypes of the LHC IR magnets.

We expect strong connection between our basic high field program and the LARP magnet R&D program.

Material and component R&D

The development of new generation accelerator magnets requires advanced superconductors, structural materials and components.

Fermilab is participating in national programs sponsored by DOE to encourage the development of improved high-field superconductors and materials in U.S. industry.

Fermilab has developed the adequate infrastructure to perform extensive superconductor, cable and material R&D in support of the magnet R&D program.

Infrastructure

- Small ovens for NB3Sn strand and cable Heat Treatment
- Sample impregnation fixtures
- Compact 28-strand cabling machine
- Sample compression fixtures (4.2-300K)
- Ic and magnetization sample holders
- compact 25 kA SC transformer
- SEM and optical microscopes
- Short Sample Test Facility
  - 15-17 T solenoid,
  - 1.5-100 K temperature insert,
  - 2 kA power supply

Nb3Sn strand R&D

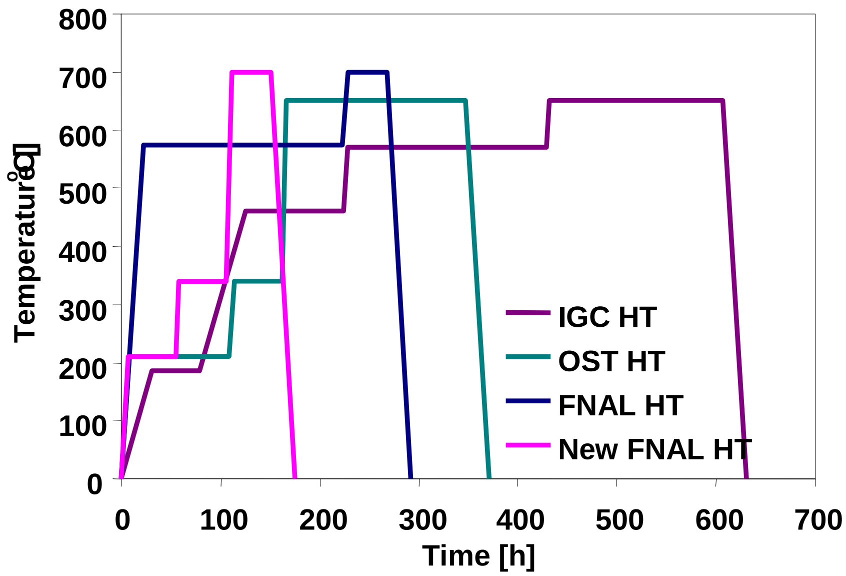
We are purchasing and studying Nb_3Sn 0.3-1.0 mm strands produced using different methods:

- "Internal Tin" (IT),
- "Distributed Tin" (DT),
- "Modified Jelly Roll" (MJR),
- "Powder in Tube" (PIT).

Strand studies include:

- $I_c(B)/J_c(B)$,
- n-value,
- RRR,
- M(B) and d_{eff}, magnetic instabilities
- SEM studies and chemical analysis,
- Strand expansion after reaction,
- Heat treatment optimization.

Heat treatment cycle optimization



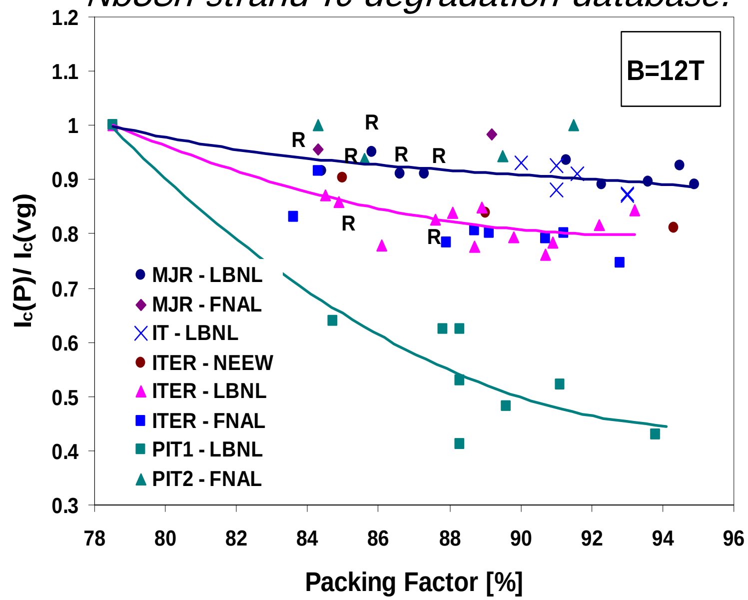
Rutherford-type cables are being developed and studied:

- different Nb_3Sn strand types
- rectangular and keystone x-section
- with and w/o SS core
- different packing factor
- one and two stage cables
- Copper stabilizers (Cu strands, Cu tape)

The studies include:

- effects of cable design on I_c degradation due to cabling, cable bending and compression,
- cable Ra measurements.

Nb3Sn strand Ic degradation database.



25 micron Cu tape (stabilizer) was wrapped around the cable using the cable insulating machine.

Insulation

Insulation is one of the most important elements of magnet design, which determines the electrical, mechanical, and thermal performance as well as lifetime of the magnet.

Wind-and-react technique imposes demanding requirements on the magnet insulation which must withstand a long high-temperature heat treatment under compression. Ceramic insulation, which meets these requirements, is being studied and optimized at Fermilab in collaboration with industry (CTD):

- Insulation: tape and cloth (strong, free of organic components)
- Low-viscosity liquid ceramic binder (improve insulation and coil mechanical properties)
- Ceramic pre-preg (life-time - 2 weeks)
  - 1st half-coil with ceramic pre-preg will be tested in April, 2003

React-and-wind technique allows using the traditional insulating materials (Kapton, fiberglass). In order to avoid the Ic degradation during the cable insulation we co-wind the insulation tapes with the cable (instead of wrapping the cable) in our racetracks and common coil magnets.

Coil impregnation materials

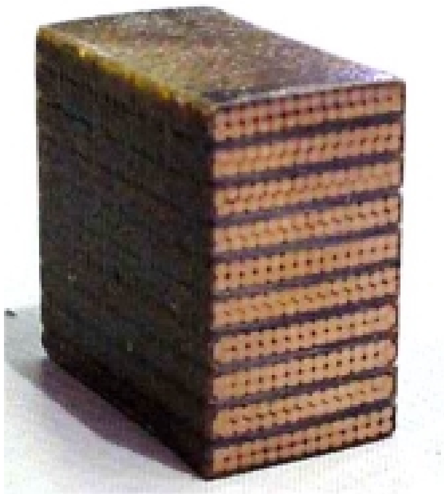
Traditionally Nb_3Sn coils are impregnated with epoxy to improve their mechanical and electrical properties. However, the radiation limit for epoxy is quite low which reduces the lifetime of the magnet.

Various commercially available polyimide solutions are being investigated to replace epoxy as an impregnation material for Nb_3Sn coils. The key factors for the applicability of these solutions are the viscosity and the potlife.

The mechanical, thermal and electrical properties of “ten-stack” samples impregnated with polyimide solution Matrimid® 5292 have been measured and compared with epoxy-impregnated samples.

- The results are very encouraging.

These studies will be continued on practice coils and then tested in model magnets.



End parts

Complicated end parts, used in traditional cos-theta coils, in case of wind-and-react techniques have to withstand the heat treatment and match the cable shape in the ends to avoid shorts.

An optimization method for metallic end parts was developed and successfully used at Fermilab together with the rapid prototyping techniques.

- Reduction of the time and the cost of end part development processes.

Water jet machining was used for end part fabrication.

- reduction of part costs by a factor of 3 (even more in the future) and manufacturing time by a factor of 10 while providing acceptable part quality.

Passive correction technique

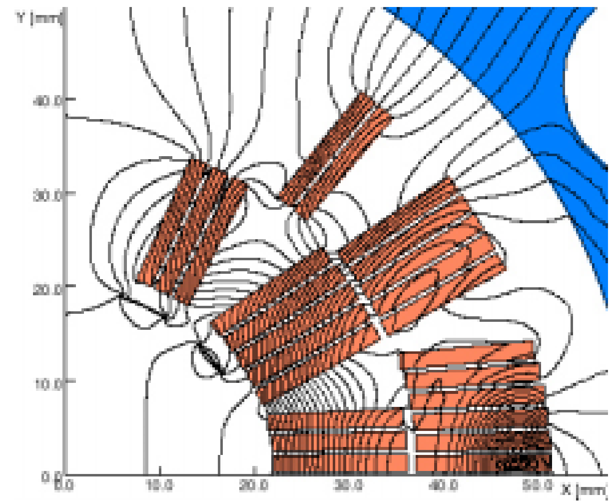
The use of Nb_3Sn conductor typically results in significant coil magnetization effects in high field magnets due to large effective filament diameters.

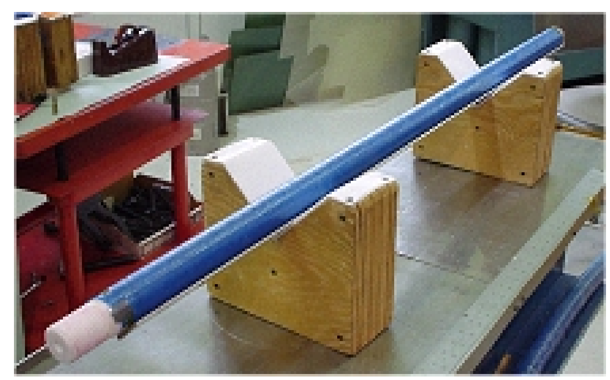
In order to reduce this effect a simple passive correction technique based on thin iron strips installed in the magnet bore or inside the magnet coil has been developed and successfully tested.

- 3 tested corrector models confirmed the design parameters

This approach offers:

- significant increase in the dynamic range of accelerator magnets,
- relaxation of the requirements on the effective filament size in Nb_3Sn strands.





Summary

Fermilab has a strong and healthy SC accelerator magnet R&D program.

Several innovative accelerator magnet design approaches and fabrication techniques have been developed and being studied experimentally. Unique experimental data related to the magnet and component performances are being collected and analyzed.

Fermilab SC Magnet R&D program will continue to be focused on the development of SC accelerator magnets for

- Tevatron needs
- LHC high-luminosity IR upgrades
- future Very Large Hadron Collider